

ON THE RADIO DICHOTOMY OF ACTIVE GALACTIC NUCLEI

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ABSTRACT

It is still a mystery why only a small fraction of active galactic nuclei (AGNs) contain relativistic jets. A strong magnetic field is a necessary ingredient for jet formation, however, the advection of the external field in a geometrically thin disk is inefficient. Gas with a small angular velocity may fall from the Bondi radius R_B nearly freely to the circularization radius R_c , and a thin accretion disk is formed within R_c . We suggest that the external magnetic field is substantially enhanced in this region, and the magnetic field at R_c can be sufficiently strong to drive outflows from the disk if the angular velocity of the gas is low at R_B . The magnetic field is efficiently dragged in the disk, because most angular momentum of the disk is removed by the outflows that lead to a significantly high radial velocity. The strong magnetic field formed in this way may accelerate jets in the region near the black hole, either by the Blandford-Payne or/and Blandford-Znajek mechanisms. We suggest that the radio dichotomy of AGNs predominantly originates from the angular velocity of the circumnuclear gas. An AGN will appear as a radio-loud (RL) one if the angular velocity of the circumnuclear gas is lower than a critical value at the Bondi radius, otherwise, it will appear as a radio-quiet (RQ) AGN. This is supported by the observations that RL nuclei are invariably hosted by core galaxies. Our model suggests that the mass growth of the black holes in RL quasars is much faster than that in RQ quasars with the same luminosity, which is consistent with the fact that the massive black holes in RL quasars are systematically a few times heavier than those in their RQ counterparts.

Subject headings: accretion, accretion disks, black hole physics, magnetic fields, galaxies: active, galaxies: jets

1. INTRODUCTION

Active galactic nuclei (AGNs) can be divided into two categories, i.e., radio-loud (RL) and radio-quiet (RQ) AGNs, according to their ratios of the radio emission to optical emission. Radio emission from RL AGNs is predominantly from the jets, and it is still a mystery why only a small fraction (about one tenth) of AGNs exhibit relativistic jets, while their appearance is quite similar to the RQ counterparts in almost all wavebands except radio wavebands (Kellermann et al. 1989; Xu et al. 1999; Cirasuolo et al. 2003; Baloković et al. 2012).

The Blandford-Znajek (BZ) and Blandford-Payne (BP) mechanisms are the most favored models of jet formation in AGNs (Blandford & Znajek 1977; Blandford & Payne 1982). The power of jets is extracted from the accretion disk or the rotating black hole by the large scale magnetic field. In the BZ mechanism, energy and angular momentum are extracted from a rotating black hole by open magnetic field lines, while the magnetic field threading the disk accelerates a small fraction of the gas in the disk to form the jets. Rapidly rotating black holes are required in RL AGNs if the BZ mechanism is responsible for the jet formation, and therefore the black hole spin is regarded as an intrinsic difference between RL and RQ AGNs (Wilson & Colbert 1995; Ye & Wang 2005; Sikora et al. 2005, 2007, 2008; Tchekhovskoy et al. 2010). However, it is still in debate the relative importance of the BP and BZ mechanisms (Livio et al. 1999; Cao 2002, 2003; Fender et al. 2010; Tchekhovskoy et al. 2011; Narayan & McClintock 2012). Although we do not know which mechanism is dominant in the jet formation of AGNs,

a strong large-scale magnetic field near the black hole is necessary for the jets in RL AGNs either with the BP or BZ mechanisms. It is reasonable to consider the strong magnetic field as a crucial factor causing the radio dichotomy in AGNs (Sikora & Begelman 2013), though the black hole spin may also play an important role in the BZ scenario. However, the numerical simulations show that almost all massive black holes will soon be spun up to rapidly spinning holes by accreting the gas in the disks (Volonteri et al. 2007), though this may be alleviated if the chaotic accretion is assumed in AGNs (King et al. 2008; Li et al. 2012; Volonteri et al. 2013). This may imply that the radio dichotomy is not solely caused by the black hole spin, instead, the radio dichotomy of AGNs may probably originate from the strong magnetic field near the black hole, i.e., an AGN appears as an RL AGN only if a strong magnetic field is present to drive relativistic jets from the region near a black hole.

It is still unclear how the strong large scale magnetic field is formed in the accretion disk. The external weak large-scale poloidal field (e.g., the field threading the interstellar medium) is suggested to be dragged inward by the accretion plasma, which is balanced by the magnetic diffusion in the disk for a steady field case (Bisnovatyi-Kogan & Ruzmaikin 1974, 1976; van Ballegooijen 1989; Lubow et al. 1994; Ogilvie & Livio 2001). This means that the configuration of the magnetic field dragged by the disk is predominantly determined by the magnetic diffusivity and the radial velocity of gas in the disk. In a conventional turbulent accretion disk, its radial velocity is mainly regulated by the kinematic viscosity ν , and the advection of the field in the disk is sensitive to the magnetic Prandtl number $P_m = \eta/\nu$, where η is the magnetic diffusivity. It was suggested that the magnetic Prandtl number should be around unity, either based on the simple estimate of the order of magnitude (Parker 1979) or the numerical simulations (e.g., Yousef et al. 2003; Lesur & Longaretti

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2009; Fromang & Stone 2009; Guan & Gammie 2009). It was found that the field can hardly be dragged inward by a thin disk ($H/R \ll 1$) because of its small radial velocity. The magnetic diffusion timescale is about the same as the viscous timescale in a steady thin disk, and the field in the inner region of the disk is not much stronger than the external weak field (Lubow et al. 1994). In order to solve this problem, a few mechanisms were suggested to alleviate the difficulty of field advection in the thin disks (Spruit & Uzdensky 2005; Lovelace et al. 2009; Guilet & Ogilvie 2012, 2013; Cao & Spruit 2013). Cao & Spruit (2013) suggested that the most angular momentum of the gas in the thin disk can be removed by the magnetically driven outflows, and the radial velocity of the disk is significantly increased. In this case, the external field can be advected efficiently by the disk with magnetic outflows.

The jets are driven by the strong magnetic field in the region near the black hole, either by the BP or/and BZ mechanisms. On the assumption that an AGN will appear as an RL AGN only if a strong magnetic field is formed near the black hole, we develop a model for the origin of the radio dichotomy of AGNs. The model is described in Section 2, and we put the results and discussion in Sections 3 and 4. The final section contains a brief summary.

2. MODEL

The gas falls almost freely toward the black hole, if the angular momentum of the gas is significantly lower than the Keplerian value at the Bondi radius. The angular momentum of the gas is roughly conserved until it approaches the circularization radius (e.g., Melia et al. 2001, but also see Bu & Yuan 2014). The external weak magnetic field is dragged in by the gas in the region between the Bondi radius and the circularization radius, due to the field flux freezing, and the field threading the gas is substantially enhanced at the circularization radius. An optically thick, geometrically thin accretion disk is formed with the circularization radius, if the gas is supplied at an appropriate rate. The angular momentum of the gas is removed by the turbulence in the accretion disk.

An effective magnetic diffusivity, corresponding to a magnetic Prandtl number of the order of unity, is caused by the turbulence in the disk. The magnetic field advection in a thin accretion disk is quite inefficient due to magnetic diffusion in such a turbulent disk, because the radial velocity of a thin disk is low. It was suggested that its radial velocity is significantly increased due to the presence of the outflows, if the angular momentum of the disk is removed predominantly by the magnetically driven outflows (see Cao & Spruit 2013, for the details). The field in such a disk with outflows is therefore efficiently advected toward the black hole. The strong magnetic field formed in this way may accelerate relativistic jets in the inner region of the disk near the black hole, either by the BP or/and BZ mechanisms. The object containing such an accretion disk with magnetic outflows may appear as an RL AGN, otherwise, it may be an RQ AGN.

2.1. Accretion of the gas in the circumnuclear region of the galaxy

The Bondi radius and the Bondi accretion rate can be calculated by the properties of the circumnuclear gas,

$$R_B = \frac{2GM_{\text{bh}}}{c_s^2}, \quad (1)$$

and

$$\dot{M} = 4\pi\lambda(GM_{\text{bh}})^2 c_s^{-3} \rho, \quad (2)$$

where the sound speed $c_s = (\gamma kT/\bar{\mu} m_p)^{1/2}$, $\gamma = 5/3$, and $\lambda = 0.25$ are adopted (e.g., Allen et al. 2006). For the gas rotating with a small angular velocity Ω_B ($\Omega_B \ll \Omega_K$, and Ω_K is the Keplerian velocity) at the Bondi radius, the gas falls almost freely to the black hole without losing its angular momentum till the circularization radius. An accretion disk is formed within the circularization radius R_c , which means that it roughly corresponds to the outer radius of the disk, i.e., $R_{\text{out}} \simeq R_c$. At the circularization radius R_c , the gas is rotating at the Keplerian velocity. This leads to

$$R_B^2 \Omega_B = R_c^2 \Omega_K(R_c), \quad (3)$$

i.e.,

$$R_c = R_B \tilde{\Omega}_B^2, \quad (4)$$

where $\tilde{\Omega}_B = \Omega_B/\Omega_K(R_B)$. Suppose a weak vertical magnetic field B_{ext} threading the gas at the Bondi radius, we can estimate the field strength at the circularization radius as

$$B(R_c) \simeq \left(\frac{R_B}{R_c}\right)^2 B_{\text{ext}}. \quad (5)$$

2.2. Advection of the magnetic field in the thin accretion disk

As the advection of the field in a thin accretion disk is quite inefficient, we consider the field advection in the disk predominantly driven by the magnetic outflows in this section (see Cao & Spruit 2013, for the details). If the magnetic field is sufficiently strong in the disk, a fraction of the gas at the disk surface (or the hot corona above the disk) may be accelerated into the outflows by the field lines threading the rotating disk. Such outflows may carry a large amount of the angular momentum of the gas in the disk, which may alter the disk structure substantially (Cao & Spruit 2013; Li 2014; Cao 2016, Cao & Lai in preparation). The radial velocity of the disk is significantly increased due to the presence of the outflows. In this case, the radial velocity of the disk with magnetic outflows is

$$V_R \simeq V_{R,\text{vis}} + V_{R,\text{m}}, \quad (6)$$

where the first term is due to the conventional turbulence in the disk, $V_R = -\alpha c_s H/R$, and the second term is contributed by the outflows,

$$V_{R,\text{m}} = -\frac{2T_m}{R\Sigma\Omega}. \quad (7)$$

For an accretion disk with magnetically driven outflows, the magnetic torque exerted by the outflows in unit area of the disk surface is

$$T_m = \frac{B_z B_\phi^s}{2\pi} R = \frac{\xi_\phi B_z^2}{2\pi} R, \quad (8)$$

where B_ϕ^s is the azimuthal component of the large scale magnetic field at the disk surface, and $\xi_\phi = B_\phi^s/B_z$. We use a parameter f_m ($f_m = V_{R,\text{m}}/V_{R,\text{vis}}$) to describe the relative importance of the outflows on the radial velocity of the disk,

$$\begin{aligned} V_R &= (1 + f_m) V_{R,\text{vis}} = \left(1 + \frac{1}{f_m}\right) V_{R,\text{m}} \\ &= -\left(1 + \frac{1}{f_m}\right) \frac{2T_m}{R\Sigma\Omega} = -\left(1 + \frac{1}{f_m}\right) \frac{B_z B_\phi^s}{\pi\Sigma\Omega}. \end{aligned} \quad (9)$$

The value of f_m is predominantly determined by the properties of the magnetically driven outflows.

The mass accretion rate of the disk at the outer radius ($R_{\text{out}} = R_c$) is

$$\dot{M} = -2\pi R_{\text{out}} \Sigma(R_{\text{out}}) V_R(R_{\text{out}}) = 2 \left(1 + \frac{1}{f_m} \right) \xi_\phi R_{\text{out}} B_z^2 \Omega^{-1}. \quad (10)$$

Substituting Equations (2), (4) and (5) into Equation (10), we obtain

$$\tilde{\Omega}_B = 0.336 \xi_\phi^{2/3} \left(1 + \frac{1}{f_m} \right)^{1/3} \times \left(\frac{T_B}{\text{keV}} \right)^{-5/6} \left(\frac{B_{\text{ext}}}{\text{mGauss}} \right)^{2/3} \left(\frac{M_{\text{bh}}}{10^8 M_\odot} \right)^{1/3} \dot{m}^{-1/3}, \quad (11)$$

where T_B is the gas temperature at R_B , and the dimensionless mass accretion rate \dot{m} is defined as

$$\dot{m} = \frac{\dot{M}}{\dot{M}_{\text{Edd}}}, \quad \dot{M}_{\text{Edd}} = 1.39 \times 10^{18} \left(\frac{M_{\text{bh}}}{M_\odot} \right) \text{ g s}^{-1}. \quad (12)$$

As the ratio ξ_ϕ is in general required to be $\lesssim 1$ (see the detailed discussion in Livio et al. 1999), we derive the first condition for efficient field advection in an accretion disk with magnetic outflows as

$$\tilde{\Omega}_B < 0.336 \left(1 + \frac{1}{f_m} \right)^{1/3} \times \left(\frac{T_B}{\text{keV}} \right)^{-5/6} \left(\frac{B_{\text{ext}}}{\text{mGauss}} \right)^{2/3} \left(\frac{M_{\text{bh}}}{10^8 M_\odot} \right)^{1/3} \dot{m}^{-1/3}, \quad (13)$$

The radial advection timescale of the magnetic field in the disk is

$$\tau_{\text{adv}} \sim \frac{R}{|V_R|}. \quad (14)$$

The magnetic diffusion timescale is

$$\tau_{\text{dif}} \sim \frac{RH\kappa_0}{\eta}, \quad (15)$$

where $\kappa_0 = B_z/B_r^s$ at the disk surface, and η is the magnetic diffusivity. For a steady magnetic field, the inclination of the field line at the disk surface can be estimated by equating the radial advection timescale with the magnetic diffusion timescale, i.e., $\tau_{\text{adv}} = \tau_{\text{dif}}$ (Lubow et al. 1994). This leads to

$$|V_R| = \frac{\alpha P_m c_s}{\kappa_0}, \quad (16)$$

where the magnetic Prandtl number $P_m = \eta/\nu$, and the viscosity $\nu = \alpha c_s H$. Comparing Equation (9) with Equation (16), we have

$$\kappa_0 = \frac{1}{1 + f_m} \frac{P_m}{\tilde{H}}, \quad (17)$$

where the relative disk thickness $\tilde{H} = H/R$. The cold gas can be accelerated by the magnetic field from the midplane of a Keplerian disk if the field line is inclined at $\lesssim 60^\circ$ ($\kappa_0 \lesssim \sqrt{3}$) with respect to the disk surface (Blandford & Payne 1982). The inclination angle could be a bit higher than 60° for the hot gas accelerated by the magnetic field with the help of the thermal pressure or/and the radiation force of the disk (Cao & Spruit 1994; Cao 2012, 2014). For a disk without

magnetic outflows, $\kappa_0 = P_m/\tilde{H} = \tilde{H}^{-1}$ if $P_m = 1$. It means that the gas cannot be magnetically accelerated by the magnetic field formed in a thin, viscously driven accretion disk, because $\kappa_0 \sim P_m/\tilde{H} \gg 1$ for a thin disk, i.e., the field lines are nearly vertically threading the disk. For a thin accretion disk predominantly driven by the outflows with $\tilde{H} = 0.1$, $\kappa_0 \simeq 1.7$ if $f_m = 5$ for a typical value of $P_m = 1$. This indicates that a strong magnetic field can be formed in a thin disk if most of its angular momentum is removed by the outflows.

The gravitational energy dissipation rate from the unit area of the disk is

$$Q_+ = \frac{1}{2} \nu \Sigma \left(R \frac{d\Omega}{dR} \right)^2, \quad (18)$$

and the mass accretion rate is

$$\dot{M} = -2\pi R \Sigma V_R = -4\pi R \left(R \frac{d\Omega}{dR} \right)^{-2} \nu^{-1} V_{R,\text{vis}} (1 + f_m) Q_+, \quad (19)$$

where Equation (9) is used. For a fixed Q_+ (disk luminosity), the mass accretion rate of an accretion disk with magnetic outflows is f_m times higher than that of a conventional viscously driven accretion disk, because most of the gravitational power of the gas in the disk is tapped into the outflows by the magnetic field.

In the outer region of the disk, the local gravity of the disk may dominate over the gravity of the black hole. In the region beyond a critical radius R_T , it may become a clumpy disk due to the gravitational instability (Hure et al. 1994; Collin & Hure 2001). The critical radius R_T can be estimated with the Toomre parameter (Toomre 1964; Goldreich & Lynden-Bell 1965),

$$Q_T = \frac{\Omega_K c_{s,d}}{2\pi G \rho_d H} = 1. \quad (20)$$

The local structure of a disk accreting at a mass rate \dot{M} with magnetically driven outflows, is the same as a standard thin disk accreting at $\dot{M}/(1 + f_m)$. The critical radius R_T can be calculated with the standard accretion disk model when the values of the parameter f_m and other disk parameters are specified.

The accretion of the clumpy disk may be driven by the collisions of the clumpies, which is similar to the case of dust torus in AGNs (Krolik & Begelman 1988). The large scale magnetic field threading the clumps may not be able to survive through repeatedly collisions. A clumpy disk region would be an obstacle for accumulation of external magnetic field. To avoid such a clumpy region in the disk, one requires $R_c < R_T$, i.e.,

$$\tilde{\Omega}_B \leq \left(\frac{R_T}{R_B} \right)^{1/2} = 0.0017 r_T^{1/2} \left(\frac{kT_B}{1 \text{ keV}} \right)^{1/2}, \quad (21)$$

where

$$r_T = \frac{R_T}{R_S}, \quad R_S = \frac{2GM_{\text{bh}}}{c^2}, \quad (22)$$

and Equation (1) is used. This is the second condition for efficient field advection in an accretion disk with magnetic outflows.

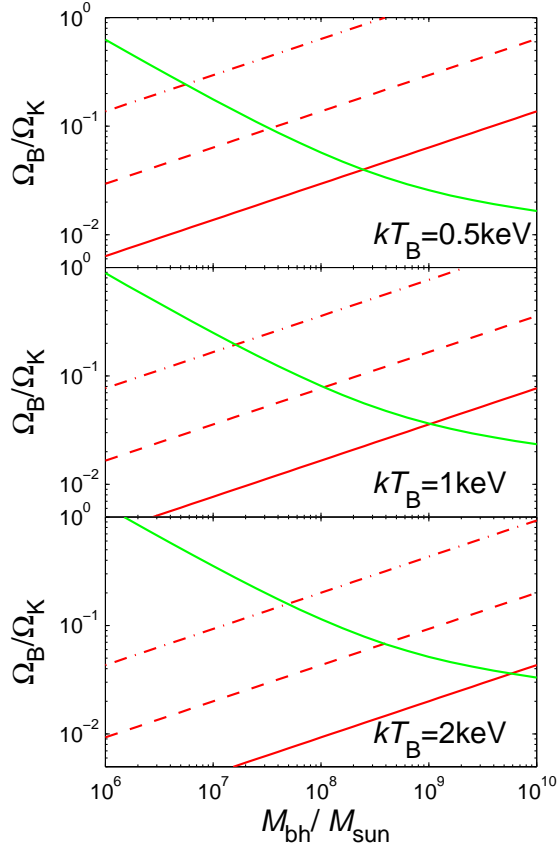


FIG. 1.— The critical angular velocities of the gas at the Bondi radius as functions of the black hole mass. The external field can be efficiently dragged in by an accretion disk with magnetic outflows only if the angular velocity of the gas is lower than both of the two critical values. All the calculations are carried out with $\dot{m} = 1$. The red lines correspond to the first condition (see Equation 13), and the green lines to the second condition for efficient field advection in the accretion disk with magnetic outflows (see Equation 21). The viscosity parameter $\alpha = 1$ is adopted in the calculations. The different types of the red lines indicate the results with different values of the external field strength at the Bondi radius (solid: 0.01 mGauss, dashed: 0.1 mGauss, and dash-dotted: 1 mGauss).

3. RESULTS

In Section 2.2, two constraints on the angular velocity of the gas at the Bondi radius are derived. The external field can be efficiently advected in an accretion disk with magnetic outflows, only if the gas with angular velocity lower than both of these two critical values at the Bondi radius. In Figure 1, we plot the results varying with the black hole mass for different gas temperatures and external field strengths. It is found that the angular velocity Ω_B is always required to be much lower than the Keplerian velocity, in order to form a strong field in the inner region of the disk, though the detailed results also vary with the other parameters. The results varying with the mass accretion rate are plotted in Figure 2. As discussed in Section 2.2, the model parameter $f_m = 5$ is adopted in all the calculations.

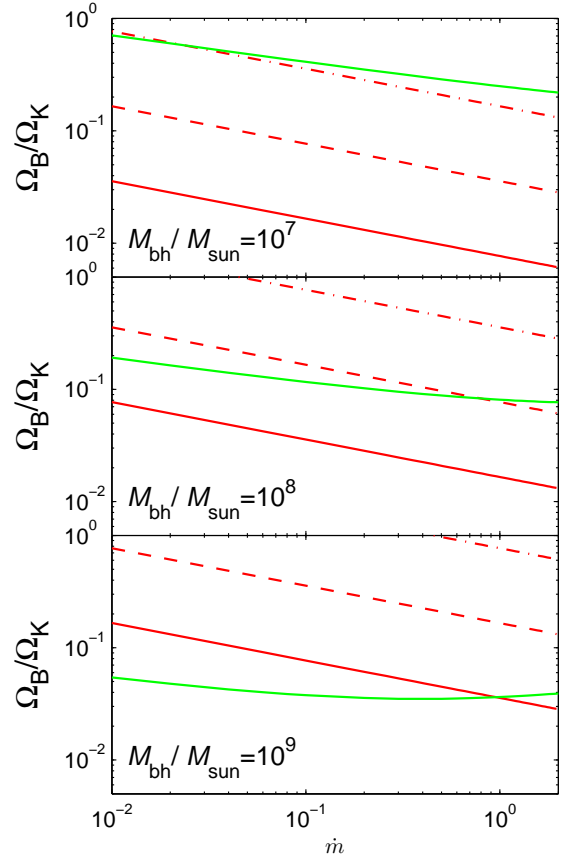


FIG. 2.— Same as Figure 1, but for the results as functions of the mass accretion rate at the Bondi radius. The circumnuclear gas temperature $kT_B = 1$ keV is adopted in the calculations.

4. DISCUSSION

There are two conditions that should be satisfied for efficient advection of the field in the thin disk with magnetic outflows. The first condition is a sufficiently strong magnetic field at the outer radius (circularization radius) of the disk (Equation 13), and the second one is the disk not being suffered from the gravitational instability, i.e., the local gravity of the disk should not dominate over the gravity of the black hole (Equation 21).

We find that RL AGNs are mainly constrained by the second condition for the AGNs with most massive black holes ($\gtrsim 10^9 M_\odot$). For the moderate or small black holes, RL AGNs are predominantly controlled by the first condition, unless for a strong external magnetic field with $B_{\text{ext}} \gtrsim 0.1$ mGauss is present (see Figure 2). In this case, the critical angular velocity of the gas at the Bondi radius, below which an AGN may appear as a RL AGN, increases with increasing black hole mass if all the other parameters are fixed.

Typical magnetic field strengths of galaxy cluster atmospheres are at the order of $\sim \mu\text{Gauss}$ (see Carilli & Taylor 2002, and the references therein), and the field strengths could be stronger for the ISM in galaxies (Thompson et al. 2006; de Gasperin et al. 2012). In the central region of our galaxy, the field strength of the gas can be as high as $\sim \text{mGauss}$ (Han & Zhang 2007). A weaker magnetic field requires the gas with a lower angular momentum at the Bondi radius for RL AGNs, because the circularization radius decreases with

decreasing angular momentum of the gas, which increases the amplification of the external magnetic field in the region between the Bondi radius and the circularization radius. Using *Chandra* X-ray observations of nine nearby radio galaxies, Allen et al. (2006) measured the temperatures of the gas at the Bondi radius of these galaxies, which are in the range of $\sim 0.5 - 1.3$ keV. We find that our main results are insensitive to the gas temperature (see Figure 1).

The radio properties of AGNs are found to be linked to their host galaxies (e.g., de Ruiter et al. 2005; Balmaverde & Capetti 2006; Capetti & Balmaverde 2006). Capetti & Balmaverde (2005) compiled a sample of AGNs in nearby early-type galaxies with available archival HST images. The sources are classified with HST images into “core” and “power-law” galaxies, and they found that the core galaxies invariably host a radio-loud nucleus (Balmaverde & Capetti 2006; Capetti & Balmaverde 2006). The core galaxies are slowly rotating and have boxy isophotes, while the power-law galaxies rotate rapidly and are disk-like (Capetti & Balmaverde 2005). This supports the model suggested in this paper that the source accreting the gas with a low angular velocity may preferentially appear as an RL AGN.

The mass accretion rate is about f_m times higher than a conventional accretion disk with the same luminosity (see Equation 19), which implies that the mass growth of the black holes in RL AGNs is much faster than that in RQ AGNs with the same luminosity. This is consistent with the fact that the massive black holes in RL quasars are systematically a few times heavier than those in their RQ counterparts (Laor 2000; McLure & Jarvis 2004). As the black hole acquires the angular momentum of the gas in the disk, the hole is spun up through accretion simultaneously. It may imply that most massive black holes in RL AGNs are rotating rapidly, and the BZ mechanism may also play an important role in RL AGNs.

Due to the mass loss in the outflows, the mass accretion rate decreases with decreasing radius in the disk. The mass loss rate in the outflows is governed by the magnetic field configuration/strength and the disk properties (e.g., disk temperature and density). The present analysis focuses on the necessary conditions for an accretion disk-outflow system, and the minimal field strength at the outer radius of the disk is derived for launching strong outflows. The properties of the outflow can be derived with the magnetic outflow solution, if suitable boundary conditions are provided (e.g., Cao & Spruit 1994; Cao 2014), which is beyond the scope of this work.

Our model implies that RL AGNs are closely associated with the magnetic outflows. The blueshifted Fe K absorption lines in the X-ray spectra of broad-line radio galaxies have been observed with *Suzaku*, which indicates the ultra-fast outflows co-exist with the relativistic jets in these sources (Tombesi et al. 2010). This seems to be consistent with our model.

Advection dominated accretion flows (ADAFs) may probably surround the black holes in low-luminosity AGNs

(Narayan & Yi 1994, 1995, see Yuan & Narayan 2014 for a recent review). Although it has already been shown that the external magnetic field can be efficiently advected in an ADAF (Cao 2011), the field enhancement in the region from the Bondi radius to the circularization radius provides a stronger field to be dragged in by the ADAF. Thus, the circumnuclear gas with a smaller angular velocity may help to form a stronger field in the inner region of the ADAF in low-luminosity AGNs.

The putative dust torus is an important ingredient of the unification model for AGN (Antonucci 1993). It is known that the mid-IR spectra and IR-to-optical flux ratios are very similar in RL and RQ quasars (e.g., Shang et al. 2011; Gupta et al. 2016), and dust torus may also be present in most RL quasars if not all. We conjecture that, the hot gas feeding the black hole co-exists with the dust clumps in a region beyond the circularization radius, and the dynamics of the hot gas is not altered significantly by the motion of the dust clumps in the torus. If this is the case, the accretion of the hot gas from the Bondi radius to the black hole can still be well described by the calculations in this paper even if a putative dust torus is present.

5. SUMMARY

The circumnuclear gas with a low angular velocity falls nearly freely from the Bondi radius to form an accretion disk within the circularization radius. The external magnetic field threading the gas is strongly amplified in this region due to the field flux freezing. For the gas with an angular velocity lower than a critical value, the field in the disk is strong enough to drive magnetic outflows, which carries away most of the angular momentum of the disk. This strongly increases the radial velocity of the disk, and therefore the field can be efficiently dragged inwards by the disk. Relativistic jets may be driven by such a large scale magnetic field through either the BP or BZ mechanism. In this case, the object may appear as an RL AGN.

If the angular velocity of the circumnuclear gas is larger than a critical value, the circularization radius (i.e., the outer radius of the disk) becomes larger, and the field cannot be amplified to a strong field in the disk to accelerate outflows. Thus, a conventional turbulence driven thin disk is formed within the circularization radius, and the advection of the field in the disk is rather inefficient. In this case, no relativistic jet is formed in the inner region of the disk, which corresponds to an RL AGN.

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REFERENCES

- Allen, S. W., Dunn, R. J. H., Fabian, A. C., Taylor, G. B., & Reynolds, C. S. 2006, *MNRAS*, 372, 21
- Antonucci, R. 1993, *ARA&A*, 31, 473
- Balmaverde, B., & Capetti, A. 2006, *A&A*, 447, 97
- Balogović, M., Smolčić, V., Ivezić, Ž., et al. 2012, *ApJ*, 759, 30
- Bisnovatyi-Kogan, G. S., & Ruzmaikin, A. A. 1974, *Ap&SS*, 28, 45
- Bisnovatyi-Kogan, G. S., & Ruzmaikin, A. A. 1976, *Ap&SS*, 42, 401
- Blandford, R. D., & Payne, D. G. 1982, *MNRAS*, 199, 883
- Blandford, R. D., & Znajek, R. L. 1977, *MNRAS*, 179, 433
- Bu, D.-F., & Yuan, F. 2014, *MNRAS*, 442, 917
- Cao, X. 2002, *MNRAS*, 332, 999
- Cao, X. 2003, *ApJ*, 599, 147
- Cao, X. 2011, *MNRAS*, 414, 1001
- Capetti, A., & Balmaverde, B. 2005, *MNRAS*, 362, 1001
- Capetti, A., & Balmaverde, B. 2006, *MNRAS*, 369, 1001
- de Ruiter, J. R., et al. 2005, *MNRAS*, 362, 1001
- Gupta, S., et al. 2016, *MNRAS*, 459, 1001
- Laor, A. 2000, *MNRAS*, 311, 1001
- McLure, R. J., & Jarvis, M. J. 2004, *MNRAS*, 350, 1001
- Narayan, R., & Yi, J. 1994, *ApJ*, 404, 1001
- Narayan, R., & Yi, J. 1995, *ApJ*, 428, 1001
- Shang, S., et al. 2011, *MNRAS*, 414, 1001
- Shang, S., et al. 2016, *MNRAS*, 459, 1001
- Spruit, A. J., & Cao, X. 1994, *MNRAS*, 271, 1001
- Tombesi, F., et al. 2010, *MNRAS*, 401, 1001
- Yuan, F., & Narayan, R. 2014, *ApJ*, 784, 1001

- Cao, X. 2011, *ApJ*, 737, 94
 Cao, X. 2012, *MNRAS*, 426, 2813
 Cao, X. 2014, *ApJ*, 783, 51
 Cao, X. 2016, *ApJ*, 817, 71
 Cao, X., & Lai, D., in preparation
 Cao, X., & Spruit, H. C. 1994, *A&A*, 287, 80
 Cao, X., & Spruit, H. C. 2013, *ApJ*, 765, 149
 Capetti, A., & Balmaverde, B. 2005, *A&A*, 440, 73
 Capetti, A., & Balmaverde, B. 2006, *A&A*, 453, 27
 Carilli, C. L., & Taylor, G. B. 2002, *ARA&A*, 40, 319
 Cirasuolo, M., Magliocchetti, M., Celotti, A., & Danese, L. 2003, *MNRAS*, 341, 993
 Collin, S., & Huré, J.-M. 2001, *A&A*, 372, 50
 de Gasperin, F., Orrú, E., Murgia, M., et al. 2012, *A&A*, 547, A56
 de Ruiter, H. R., Parma, P., Capetti, A., et al. 2005, *A&A*, 439, 487
 Fender, R. P., Gallo, E., & Russell, D. 2010, *MNRAS*, 406, 1425
 Fromang, S., & Stone, J. M. 2009, *A&A*, 507, 19
 Goldreich, P., & Lynden-Bell, D. 1965, *MNRAS*, 130, 97
 Guan, X., & Gammie, C. F. 2009, *ApJ*, 697, 1901
 Guilet, J., & Ogilvie, G. I. 2012, *MNRAS*, 424, 2097
 Guilet, J., & Ogilvie, G. I. 2013, *MNRAS*, 430, 822
 Gupta, M., Sikora, M., & Nalewajko, K. 2016, *MNRAS*, 461, 2346
 Han, J. L., & Zhang, J. S. 2007, *A&A*, 464, 609
 Hure, J.-M., Collin-Souffrin, S., Le Bourlot, J., & Pineau des Forets, G. 1994, *A&A*, 290, 19
 Kellermann, K. I., Sramek, R., Schmidt, M., Shaffer, D. B., & Green, R. 1989, *AJ*, 98, 1195
 King, A. R., Pringle, J. E., & Hofmann, J. A. 2008, *MNRAS*, 385, 1621
 Krolik, J. H., & Begelman, M. C. 1988, *ApJ*, 329, 702
 Laor, A. 2000, *ApJ*, 543, L111
 Lesur, G., & Longaretti, P.-Y. 2009, *A&A*, 504, 309
 Li, S.-L. 2014, *ApJ*, 788, 71
 Li, Y.-R., Wang, J.-M., & Ho, L. C. 2012, *ApJ*, 749, 187
 Livio, M., Ogilvie, G. I., & Pringle, J. E. 1999, *ApJ*, 512, 100
 Lovelace, R. V. E., Rothstein, D. M., & Bisnovatyi-Kogan, G. S. 2009, *ApJ*, 701, 885
 Lubow, S. H., Papaloizou, J. C. B., & Pringle, J. E. 1994, *MNRAS*, 267, 235
 McLure, R. J., & Jarvis, M. J. 2004, *MNRAS*, 353, L45
 Melia, F., Liu, S., & Coker, R. 2001, *ApJ*, 553, 146
 Narayan, R., & McClintock, J. E. 2012, *MNRAS*, 419, L69
 Narayan, R., & Yi, I. 1994, *ApJ*, 428, L13
 Narayan, R., & Yi, I. 1995, *ApJ*, 452, 710
 Ogilvie, G. I., & Livio, M. 2001, *ApJ*, 553, 158
 Parker, E. N. 1979, in Chapter 17, *Cosmical Magnetic Fields* (Oxford:Clarendon Press)
 Shang, Z., Brotherton, M. S., Wills, B. J., et al. 2011, *ApJS*, 196, 2
 Sikora, M., & Begelman, M. C. 2013, *ApJ*, 764, L24
 Sikora, M., Begelman, M. C., Madejski, G. M., & Lasota, J.-P. 2005, *ApJ*, 625, 72
 Sikora, M., Stawarz, L., & Lasota, J.-P. 2007, *ApJ*, 658, 815
 Sikora, M., Stawarz, L., & Lasota, J.-P. 2008, *New A Rev.*, 51, 891
 Spruit, H. C., & Uzdensky, D. A. 2005, *ApJ*, 629, 960
 Tchekhovskoy, A., Narayan, R., & McKinney, J. C. 2010, *ApJ*, 711, 50
 Tchekhovskoy, A., Narayan, R., & McKinney, J. C. 2011, *MNRAS*, 418, L79
 Thompson, T. A., Quataert, E., Waxman, E., Murray, N., & Martin, C. L. 2006, *ApJ*, 645, 186
 Tombesi, F., Sambruna, R. M., Reeves, J. N., et al. 2010, *ApJ*, 719, 700
 Toomre, A. 1964, *ApJ*, 139, 1217
 van Ballegoijen, A. A. 1989, in *Accretion Disks and Magnetic Fields in Astrophysics*, ed. G. Belvedere (ASSL Vol. 156; Dordrecht: Kluwer), 99
 Volonteri, M., Sikora, M., & Lasota, J.-P. 2007, *ApJ*, 667, 704
 Volonteri, M., Sikora, M., Lasota, J.-P., & Merloni, A. 2013, *ApJ*, 775, 94
 Wilson, A. S., & Colbert, E. J. M. 1995, *ApJ*, 438, 62
 Xu, C., Livio, M., & Baum, S. 1999, *AJ*, 118, 1169
 Ye, Y.-C., & Wang, D.-X. 2005, *MNRAS*, 357, 1155
 Yousef, T. A., Brandenburg, A., & Rüdiger, G. 2003, *A&A*, 411, 321
 Yuan, F., & Narayan, R. 2014, *ARA&A*, 52, 529